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Leptogenesis at the TeV scale

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We consider a generic model with four gauge singlets which generates successfully the right amount of baryon asymmetry through leptogenesis at the TeV scale. It also reproduces left-handed neutrino masses compatible with present data.
In the present work, we perform a study of thermal production mechanisms of the lightest right-handed neutrino N_1 responsible for the lepton asymmetry taking into account all dominant processes (decays, $\Delta L = 1$ and $\Delta L = 2$ scatterings) by solving the full Boltzmann equations.

Introduction

The baryon asymmetry of the universe (BAU) plays a special role in both particle physics and cosmology. This fact is usually expressed in terms of the ratio of the baryon number density n_B to the entropy s of the universe. The latest measure from WMAP for this ratio is determined to be [1]

$$\eta = \frac{n_B - n_{\bar{B}}}{s} \simeq \frac{n_B}{s} = 6.5^{+0.4}_{-0.3} \times 10^{-10} \ . \tag{1}$$

A viable model of baryogenesis must fulfil Sakharov's conditions [2], namely it must contain:

- Baryon number violation
- C and CP violation

[a] Presented the invited talk.

- A deviation from thermal equilibrium.

It is well known that in the Standard model (SM) the baryonic (B) and leptonic (L) numbers are violated at the quantum level and that there is CP violation in the quark sector. However, it was established that the asymmetry created in this sector is not enough to explain the observed BAU, see for example [3].
It is now established that neutrinos have non vanishing masses (Superkamiokande [4], SNO [5], ...). One of the most interesting consequences of this, is the possibility to generate the BAU through leptogenesis via the non equilibrium decay of heavy right-handed (RH) neutrinos [6]. Including such heavy particles gives us the possibility to generate natural small masses to the neutrinos via the seesaw mechanism [7], and leads to CP violation in the leptonic sector [8]. This leptonic asymmetry is partially converted into a baryonic asymmetry through non perturbative effective sphaleron interactions [9]. It was shown that a lower bound on the mass of the added RH neutrinos can be placed $M \sim 10^8$ GeV [10,11] for a minimal extension of the SM with 3 RH neutrinos.
Nevertheless, it is expected that new physics will appear not so far from the TeV scale. So, considering a model of leptogenesis at this scale can be an interesting alternative, and can be indirectly tested in upcoming experiments. The author of ref. [12] has illustrated some difficulties which can plague leptogenesis models at the TeV scale, namely: a) obtaining adequate values of the lepton asymmetry given the constraint from the out-of-equilibrium decay, b) damping effects if the decaying particle has gauge interactions, c)an extremely small value of the neutrino masses, or d)it is difficult to have a model in which the same interactions produce the asymmetry and non-zero neutrino masses. The author also discusses possible enhancement mechanisms which could overcome the above mentioned difficulties . Other possible TeV scale models have been also discussed in Refs. [13,14,15].
In the present work, by solving Boltzmann equations (BE) for a generic model proposed in ref.[16], we perform a study of the thermal production mechanism related to the lightest RH neutrino inducing the leptonic asymmetry. In section 2, we present the model and its m ain features, in section 3, we solve the BE for, both a toy model with only two generations, and our generic model with four gauge singlets, and finally in section 4 we present our conclusions.

The Model

The model proposed in [16] is based on the SM with a minimal extension by adding a fourth generation which satisfies the LEP constraints and four gauge singlets ν_R. The Lagrangian of the model is given by [16]

$$L = L_{SM} + \bar{\psi}_{R_I} i\partial\!\!\!/\, \psi_{R_I} - \frac{M_{N_I}}{2}(\bar{\psi}^c_{R_I}\psi_{R_I} + h.c.) - (Y^{\nu}_{IJ}\bar{L}_J\psi_{R_I}\phi + h.c.) \ , \tag{2}$$

where ψ_{R_I} are two-component spinors describing the RH neutrinos and we define a Majorana 4-component spinor, $N_I = \psi_{R_I} + \psi^c_{R_I}$. Our index I runs from 1 to 4. The fourth component of L_I corresponds to a left-handed (LH) lepton doublet which must satisfy the LEP constraints from the Z-width on a fourth LH neutrino [17]. The Y_{IJ} are Yukawa couplings and the field ϕ is the (SM) Higgs boson doublet whose vacuum expectation value is denoted by v. We work in the basis in which the mass matrix for the RH neutrinos M is diagonal and real,

$$M = diag(M_1, M_2, M_3, M_4) \tag{3}$$

and define $m_D = Y_\nu v$. The neutrino mass matrix for the LH neutrinos is given by,

$$m_\nu = m_D^T M^{-1} m_D = Y_\nu^\dagger M^{-1} Y_\nu v^2 \ . \tag{4}$$

It is clear here that the LH neutrinos get small masses via the seesaw mechanism when the RH neutrinos masses are large or alternatively for $M_i \sim$ TeV for values of the neutrino Yukawa couplings on the order of the electron Yukawa coupling.
The CP asymmetry arises from the interference between tree level and one-loop diagrams (self-energy and vertex corrections), and the CP violation parameter is given by (for more details see ref.[8])

$$\epsilon_I = \frac{1}{(8\pi)} \frac{1}{[Y_\nu^\dagger Y_\nu]_{II}} \sum_J Im[Y_\nu^\dagger Y_\nu]^2_{IJ} \left[f\left(\frac{M_J^2}{M_I^2}\right) + g\left(\frac{M_J^2}{M_I^2}\right)\right] , \tag{5}$$

where

$$\begin{aligned} f(x) &= \sqrt{x}[1-(1+x)\ln\frac{1+x}{x}], \\ g(x) &= \frac{\sqrt{x}}{1-x}. \end{aligned} \tag{6}$$

The ratio $\eta = Y_B = \frac{n_B}{s}$ is related to leptonic asymmetry ratio $Y_L = \frac{n_L}{s}$ by

$$Y_B = -\left(\frac{8N_F + 4N_H}{22N_F + 13N_H}\right) Y_L, \tag{7}$$

where N_H is the number of Higgs doublets and N_F is the number of fermionic families.

Boltzmann Equations

The production of a baryonic or leptonic asymmetry is an out-of-equilibrium process which is usually analysed using Boltzmann Equations[18]. The main processes in the thermal bath of the early universe are decays, inverse decays of the RH neutrinos, and the lepton number violation $\Delta L = 1$ and $\Delta L = 2$, Higgs and RH neutrinos exchange scattering processes, respectively.
The first BE, which corresponds to the evolution of the abundance[b] of the lightest RH neutrino Y_{N_1} involving the decays, inverse decays and $\Delta L = 1$ processes is given by

$$\frac{dY_{N_1}}{dz} = -\frac{z}{sH(M_1)}(\frac{Y_{N_1}}{Y_N^{eq}} - 1)(\gamma_D + \gamma_S) \tag{8}$$

where $z = M_1/T$ and γ_D, γ_S are the interaction rates for the decay and scattering $\Delta L = 1$ contributions, respectively.
The BE for the lepton asymmetry is given by

$$\frac{dY_L}{dz} = -\frac{z}{sH(M_1)}[\epsilon_1 \gamma_D(\frac{Y_{N_1}}{Y_N^{eq}} - 1) + \gamma_W \frac{Y_L}{Y_L^{eq}}] \tag{9}$$

where ϵ_1 is the CP violation parameter given by eq.(5) and γ_W, which is function of γ_D and γ_S and $\Delta L = 2$ interaction rate processes, is a washout factor responsible for the damping of the produced asymmetry. Explicit expressions of the interaction rates γ_D , γ_S and γ_W can be found in for example refs. [19,20] (and references therein) where one can easily extend them to our model.

[b] We suppose that the asymmetry is due only to the decay of the lightest RH neutrino N_1.

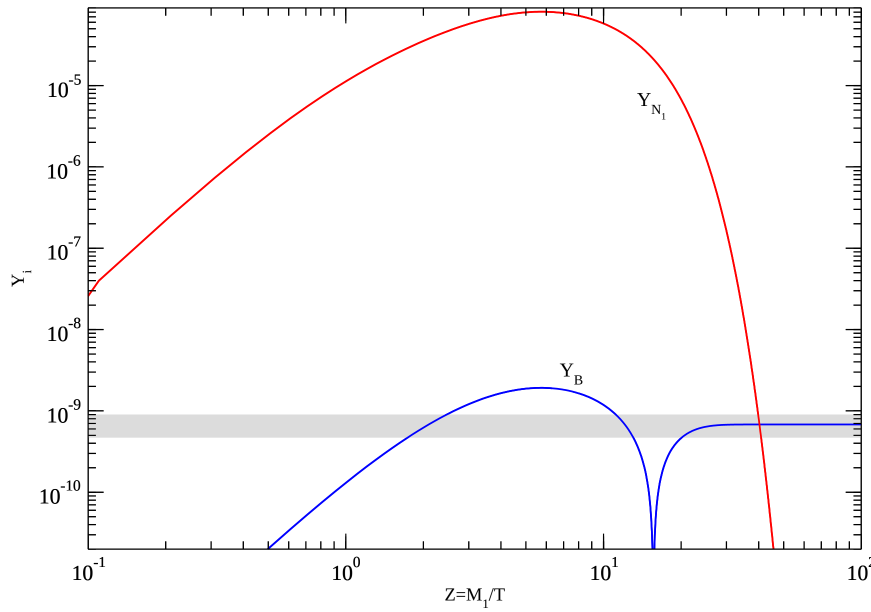

Figure 1: Toy model abundance Y_{N_1} and the baryon asymmetry Y_B.

Toy Model

In ref. [16], the case of two generations as a toy model was considered and it was estimated that this toy model fits the right amount of Y_B. In this section, we solve eqns. (8) and (9), for one possible texture for the neutrino Yukawa coupling matrix. This texture allows us to illustrate the interplay of the different terms which contribute to the CP asymmetry in eq. (5), and has the form

$$Y_\nu = \begin{pmatrix} \epsilon & \epsilon \\ \alpha & 1 \end{pmatrix}. \tag{10}$$

In figure 1 we plot the integration of the BE for the abundance Y_{N_1} and the baryon asymmetry $|Y_B|$ as a function of $z = M_1/T$ for the values of $M_1 = 450$ GeV, $M_2 = 650$ GeV, $\epsilon = 1.6(1-i)\times 10^{-11}$ and $\alpha = 1.6\times 10^{-7}(1-10^{-4}i)$. We are choosing these values for the sake of illustration, as they allow us to satisfy the constraints on neutrino masses. For instance, applying the seesaw mechanism with the same set of parameters, we obtain a heavy left-handed neutrino with a mass above 45 GeV, as expected, and a light one with a mass of the order of 10^{-4} eV. Finally, the generated values for the CP parameter and the final baryon asymmetry are $|\epsilon_1| \simeq 2.5\times 10^{-5}$ and $\eta_B \simeq 6.7\times 10^{-10}$, respectively.

Four generations

We now generalise the texture Y_ν of the toy model to the case of 4 generations :

$$Y_\nu = C \begin{pmatrix} \epsilon & \epsilon & \epsilon & \epsilon \\ \epsilon & 1 & 1 & 0 \\ \epsilon & 1 & 1 & 0 \\ \alpha & 0 & 0 & 1/C \end{pmatrix}. \tag{11}$$

This will induce to first order the following mass matrix for the light LH neutrinos

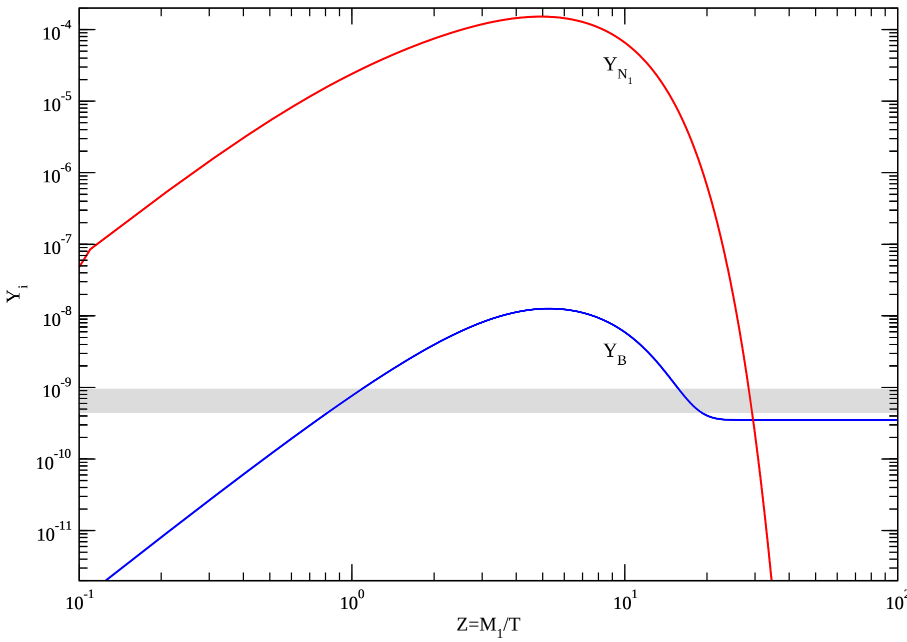

Figure 2: Abundance Y_{N_1} and the baryon asymmetry Y_B for the four generation model.

$$m_\nu = C^2 \frac{v^2}{M} \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}, \tag{12}$$

which is a simple form of the light neutrino mass matrix which can account for all data [21,22]. C is a small number that makes C^2v^2/M to be of the correct order of magnitude.

In figure 2 we plot the solutions of the BE as a function of $z = M_1/T$ for the following set of parameters, chosen for illustration : $M_1 = 450$ GeV, $M_2 = 2 \times 10^5$ GeV, $M_3 = 10^6$ GeV $M_4 = 650$ GeV, $\epsilon = 2.4 \times 10^{-4}(1 - .01i)$, $\alpha = 1.2 \times 10^{-3}(1 - i)$ and $C = 5 \times 10^{-5}$. Applying the seesaw mechanism to our model for the same values of the parameters we obtain a heavy left-handed neutrino with a mass above 45 GeV, and the light neutrinos with masses of the order of 10^{-1} eV to 10^{-7} eV. The generated values for the CP and the baryon asymmetries obtained for this texture are $|\epsilon_1| \simeq 6.8 \times 10^{-5}$ and $\eta_B \simeq 3.4 \times 10^{-10}$ respectively.

Conclusion

In this work, we have analysed the possibility of leptogenesis at the TeV scale for a generic model. By solving the BE equations for the production of the heavy RH Majorana neutrinos and the lepton asymmetry at this scale, we have shown that lepton (baryon) asymmetry can be produced. This model also satisfies all constraints from low energy data and cosmology.

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